Assessing spatial and temporal changes in the landscape vulnerability in the Kaliningrad region as an element of sustainable spatial planning

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ECOLOGY

ASSESSING SPATIAL AND TEMPORAL CHANGES IN THE LANDSCAPE VULNERABILITY IN THE KALININGRAD REGION AS AN ELEMENT OF SUSTAINABLE SPATIAL PLANNING

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The relevance of applied regional studies aimed at solving problems of adapting the nature management and spatial planning system to the current conditions of natural landscape transformation is based on the widespread interest in this topic from Russian and international researchers. Environmental approaches, which gained currency at the legislative level elsewhere in Europe, are virtually absent in the Russian system of spatial planning. This results in the emergence of and increase in the number of nature management conflicts at the regional and local levels and creates problems for using advanced international experience in problem solving. This study aims to establish a methodology for a comprehensive assessment of the Kaliningrad region's territory according to the degree of landscape vulnerability to the anthropogenic impact in spatial and temporal aspects. In practical terms, this study demonstrates the possibility of introducing environmental approaches into the system of regional spatial planning in view of the geoecological, economic, geographical, and historical factors. The key result of this study is the preparation of cartographic documents describing changes in landscape vulnerability of the Kaliningrad region. These documents serve as the basis for proposals aimed at optimising the regional nature management system. The findings of the study make it possible to augment the existing approaches to spatial planning in the Kaliningrad region and its municipalities.

Key words: landscape, vulnerability, Kaliningrad region, Curonian spit, GIS, nature management, spatial planning

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Intensive human use of the Baltic region's coastal territories emphasised the conflict between environmental and economic interests of their development. The popular European concept of sustainable regional development suggesting the introduction of environmental aspects into the spatial planning process at legal and administrative levels is gaining wide currency in Russian studies. Therefore, geoecological assessments of current condition of ecosystems make it possible to track changes brought about by human use. In the past decade, this area has been rapidly developing in Russia in line with political and administrative transformations of the regional nature management and spatial planning.

Keen interest in this topic is generated by the need to consider regional socioeconomic and ecological-geographic characteristics in order to develop balanced scenarios for regional development in Russia. A number of model regions requiring special environmental protection efforts (for example, Lake Baikal) launched projects aimed to emphasise the significance of environmental component in developing and amending spatial planning documents.

These initiatives showed that most Russian regions did not pay sufficient attention to mechanisms for integrating environmental approaches into regional spatial planning at either legal or administrative levels. Thus, the existing conflicts between nature management and economic entities intensify, whereas the balance of interests regulated by law is tipped in favour of the latter. This is manifested in the selective approach to the zoning of protected elements (sanitary barrier zones, water protection zones, etc.), which hamper identifying protection priorities and analysing the actual landscape of the studied territory [18].

The Urban Code of the Russian Federation (2004) has elements regulating conditions for sustainable development of territories in view of environmental, economic, and other factors. However, environmental factors are not considered independently but they rather fulfil the function of limitations instrumental in identifying zones suitable for design and engineering works. This state of affairs is not particularly promising. There is a need for new standards of landscape spatial planning taking into account ecological components of the environment as immediate object of protection and conservation [20].

In some European countries, the applied aspects of landscape spatial planning with its multi-criteria assessment system developed into an independent area — multi-criteria decision-making and spatial decision analysis. These two notions suggest analysing a complex spatial problem through dividing it into integral elements, studying these elements, and integrating them for making a rational decision [24]. Such practices are used when assessing the consequences of major managerial decisions relating to the development of urban territories, large infrastructure projects, etc. [25; 27]. Employing GIS technology in these processes makes it possible to consolidate large arrays of geoecological, social, economic, and other spatial data for reaching a rational decision in each case. This approach helps researchers to find common ground with officials responsible for developing proposals and recommendations for various nature conservation and planning areas.

In the conditions of increasing anthropogenic pressure, the Russian system of spatial planning cannot meet contemporary challenges and ensure substantial regional development. Solving such problems does not always require a revision of all planning standards, which can take decades. However, there is a need for a universal tool that will make it possible to combine elements of integrated assessment techniques and environmental factors — features of natural landscapes.

One of such tools is multi-criteria assessment of natural systems reflecting their general geo-ecological condition — calculation of landscape vulnerability to anthropogenic pressures. Taking into account the integrated indices at all stages of designing and exploiting industrial and infrastructural facilities makes it possible to decrease pressure on the environmental components and ensure sustainable development of a territory [13]. In view of the plans to launch large-scale construction of tourism and sports infrastructure in the Kaliningrad region, certain industries and the energy sector started to pay special attention to this issue.

The methodology for assessing the vulnerability of Kaliningrad landscapes to anthropogenic pressure includes several components described in a number of earlier published works [9; 12; 13]. Therefore, there is a need to consider key aspects of this methodology:

— definition of the notion of ecosystem vulnerability;

— algorithm for calculating an integrated vulnerability index;

— structure and results of using the 'Assessment vulnerability of Kaliningrad landscapes to anthropogenic pressures' GIS for assessing spatial and temporal variability of the integrated index.

The first stage of developing an integrated methodology for assessing the vulnerability of ecosystems to anthropogenic pressures requires distinguishing between the related notions of 'vulnerability', 'sustainability', and 'sensitivity'. The use of these terms was analysed in Russian and international studies, which made it possible to identify their differences and similarities and to distinguish between them depending on the structure of the object of study:

— *sustainability* [10; 21] is the capacity of a system to withstand external shocks maintaining its characteristics;

— *sensitivity* [4; 19; 26] is a type of response of ecosystem to external shocks, the intensity of response corresponds to the scope and scale of changes and their consequences taking place in the ecosystem. Otherwise, sensitivity is understood as the capacity of natural components across the territory to change its properties and characteristics under external impacts;

— *vulnerability* [5; 25] is an independent characteristic of geo-ecological condition of ecosystems reflecting the probability of severance of functional ties between system-building components. Therefore, environmental vulnerability is defined as the ability of ecosystem components to change under the influence of external shocks the disturbance of its structure and functioning.

The use of the notions of sustainability, sensitivity, and vulnerability depends on two factors: the structure of study object and selection of assessment criteria. The terms ‘sustainability’ and ‘sensitivity’ are used in relation to integrated organised objects — organisms, populations, ecosystems, geosystems. ‘Vulnerability’ is a characteristic of discrete objects — administrative unite, territories, etc. Their condition should be assessed based on changes in qualitative indicators. This approach rests on the assumption that the key features of biological structure of ecosystem can be described using a system of abiotic indicators [19].

In this work, vulnerability assessment will be understood as the process of identifying ecosystems with a strong response to anthropogenic pressure to prevent or minimise the probability of exposure to anthropogenic contaminants.

The basic algorithm for calculating the integrated vulnerability index is based on the multi-criteria approach described in the works of V. V. Dmitriev [5; 6], where it was applied to the conditions of information deficit. The algorithm contains the following operations.

Stage 1. Selection of m criteria $x_1, \ldots, x_m$ reflecting different parameters of the studied properties.

Stage 2. Valuation of indices to obtain dimensionless indices $q_1, \ldots, q_m$, $0 \le q_i \le 1$.

Stage 3. Introduction of a function aggregating valuated indices $q_1, \ldots, q_m$ into the integrated index $Q = Q(q)$:

$$Q = Q(q, w) = Q(q_1, \ldots, q_m; w_q, \ldots, w_m) = \sum q_i w_i \,. \tag{1}$$

Stage 4. Calculation of weighted coefficients $w = (w_1, \ldots, w_m)$ — non-negative weights defining the significance (priority) of individual parameters for assessing the priority ($w_1 + \ldots + w_m = 1$) in view of expert information on their weights:

— ordinal — *OI*:

$$OI = \{w_r > w_s, w_u = w_v, \ldots r, s, u, v, \in \{1, \ldots m\}\}; \tag{2}$$

— interval — *II*:

$$II = \{0 \le a_i \le w_i \le b_i \le 1\{1, \ldots m\}\}; \tag{3}$$

Stage 5. A transition to an integrated assessment $Q\ (q; I) = MQ\ (q; I)$:

$$\overline{Q^{(j)}}(I) = \overline{Q}(q^{(j)}; I) = \overline{Q}(q^{(j)}, \overline{w}(I)) = \frac{1}{N(m, n; I)} \sum_{t=1}^{N(m,n;I)} Q^{(t)}(q^{(j)})\,. \tag{4}$$

The need to apply an integrated graded index was met through introducing weighted coefficients calculated using the method of randomised aggregate indices [22].

The selection and justification of criteria for assessing vulnerability of ecosystems based on the data on predominant anthropogenic pressures characteristic of the studies area.

An analysis of statistical materials [11] shows that the major anthropogenic impacts on the natural landscapes of the Kaliningrad region are physical and chemical. The chemical impact is pollution of the environment or its components with different soluble and infiltrated chemical pollutants — carbohydrates, psychoactive substances, heavy metals, etc. [17]. The physical impact is a combination of gravitational forces leading to the destruction and thickening of and changes in the structure of a landscape component.

In view of the general structure of Kaliningrad natural landscapes, one can assume that the criteria for vulnerability assessment should include hydrological, geomorphological, soil, and other parameters. They also should be consistent with the following hypothesis [13]:

1. Key functional components of a landscape are energy exchange, hydrological cycle, and geochemical circulation. Ensuring substance and energy flows is one of the key functions of a landscape.
2. Abiotic nature shapes conditions for the following developing of the living environment [15]. Key features of the biotic landscape structure can be correlated with abiotic indicators [7].

A parameter matrix (table 1) was developed for the conditions of the Kaliningrad region. Weighted coefficients were calculated for 20 information scenarios of distribution of assessment parameter significance. Based on these data, two groups of parameters were identified — major (distance to a water body, level of groundwater, soil texture) and secondary (spawning and conservation states, surface slope, river network density, and land use). The numerical value of major weighted coefficients is 0.25, that of secondary 0.05.

Table 1

Parameter matrix of landscape vulnerability to anthropogenic pressure

Parameter	Vulnerability category				
	High	Increased	Moderate	Reduced	Low
Distance to a water body (m)	0—200	201—400	401—600	601—800	801—1000
Surface slope (˚)	20—17	16—13	12—9	8—5	4—0
River network density (km/km²)	1.4 -1.25	1.24—1.11	1.10—0.96	0.95—0.80	0.79—0.60
Spawning status	Yes		No		
Conservation status	Yes		No		
Groundwater level (m)	0.5—2.0	2.1—4.0	4.1—6.0	6.1—8.0	8.1—10.0
Soil texture	sand	loamy sand	sandy cay loam	sandy clay	clay
Land type	Wetland	Forest		Meadow (agriculture)	

Source: [8].

This methodology was applied using the ‘Assessment of vulnerability of the Kaliningrad region’s landscape to anthropogenic pressures’ GIS based on the ESRI ArcGIS software [14].

The GIS structure included digital images at a scale of 1:500 000 created based on field and desktop studies (point sources of anthropogenic sources) and source maps [2].

Three types of objects were considered as point sources of anthropogenic pressure in the Kaliningrad region — oil deposits, sand and gravel quarries, and landfills. This selection is explained by their scale, spatial representation, and exploitation rates, as well as associated potential and existing environmental problems. Deciphering satellite images made it possible to localise and digitalise 80 anthropogenic objects from these categories.

These calculations made it possible to create a regional model of location of areas of landscape vulnerability to anthropogenic pressure, i. e. areas of control classified by vulnerability categories depending on the integrated index value with landscape types typical of each category (Fig. 1).

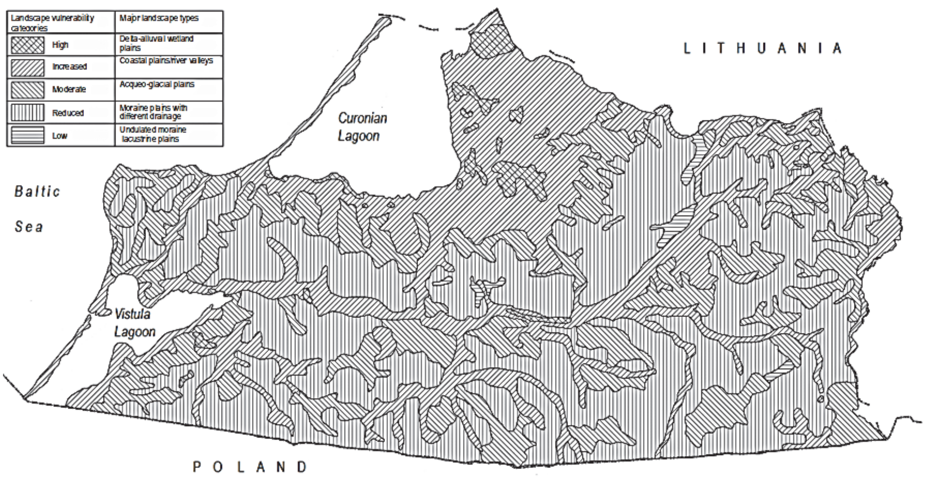


Fig. 1. Regional model of areas of landscape vulnerability
to anthropogenic pressures in the Kaliningrad region (by categories)

In absolute numbers and percentage, the ratio of areas of landscapes belonging to different vulnerability categories to the total area of the region is as follows: high vulnerability — 270 km² (2%), increased — 4,076 km² (30%), moderate — 3,029 km² (23%), reduced — 5,828 km² (44%), low — 97 km² (1%). An analysis of the data obtained suggests that an area of vulnerability of a certain category can extend to several landscape units. At the same time, different vulnerability levels are characteristic of different landscapes. The most vulnerable ones are coastal sea plains, river valleys and delta alluvial-wetland plains; the least vulnerable undulated moraine and lacustrine plains.

The final maps of areas of landscape vulnerability to chemical and physical impact make it possible to identify territories that are more or less suitable for industrial facilities — potential sources of the negative impact. As a spatial planning tool, these schemes can supplement the existing approaches to spatial planning at the regional or municipal level [14].

A spatial analysis of location of existing point sources of anthropogenic pressure — landfills, sand and gravel quarries, and oil deposits — was carried out to demonstrate possible practical applications of the proposed assessment of landscape vulnerability to anthropogenic pressures. Considering these data made it possible to identify the potential hazard to the components of natural environment (Fig. 2).

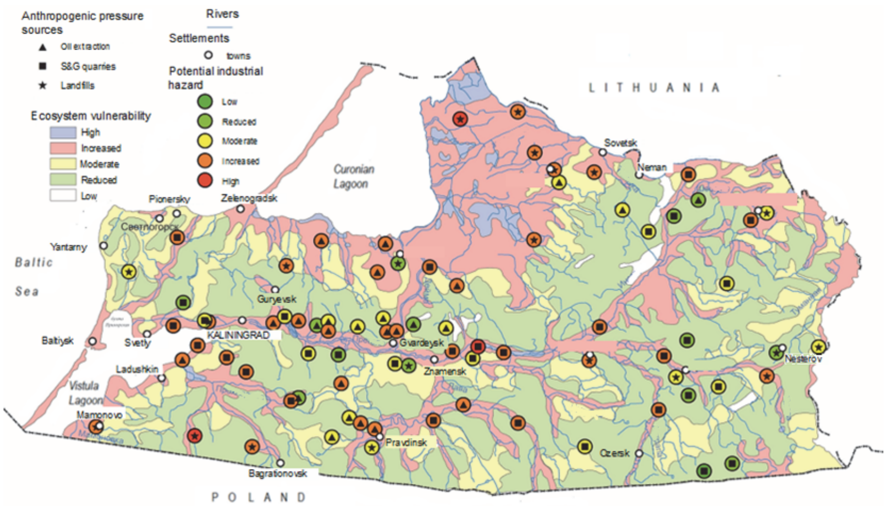


Fig. 2. Differentiation of points sources of anthropogenic pressure by potential hazard to the natural landscapes of the Kaliningrad region

All these objects of anthropogenic pressure were classified according to the vulnerability area into five categories. Each category was assigned a potential hazard level. High vulnerability corresponds to level 1 (high level of hazard) and low to level 5 (low level) (table 2).

Table 2

Distribution of anthropogenic pressure sources by potential hazard levels in the Kaliningrad region

Source category	Potential hazard level					Total
	1st (high)	2nd (increased)	3rd (moderate)	4th (reduced)	5th (low)	
Oil deposits	0	14	8	4	0	26
Quarries	1	16	9	7	0	33
Landfill	2	11	5	3	0	21
Total, by categories	3	41	22	14	0	80

By the distribution pattern, high and increased hazard levels are characteristic of more than a half of anthropogenic pressure sources (55 %), moderate and reduced levels of 45 % of the objects. This makes it necessary for the companies belonging to the most hazardous categories to develop additional conservation measures and to introduce environmental approaches into the system of spatial planning in order to prevent or minimise the risk of locating industrial facilities in highly vulnerable landscapes.

Another area of practical application is assessing the temporal changes in the vulnerability of natural landscapes. The historical aspect makes it possible to trace changes in the characteristics of a territory over a certain period and to identify what factors triggered landscape transformations from the perspective of nature management. Such approach makes it possible to examine the development scenario for the selected territory and adjust it in line with modern spatial planning. The Curonian Spit was selected as a model area. Its natural landscapes are unique, being the youngest in region. Neither vegetation, nor relief has been affected by human occupation [1; 23].

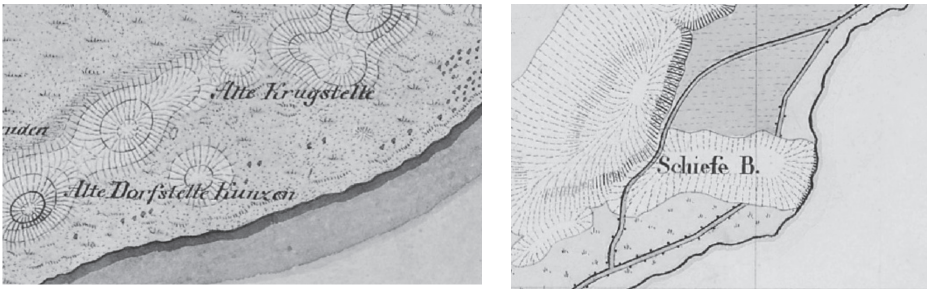
The transformation of the Curonian Spit's landscapes was caused not only by the construction of tourist and recreational facilities, but also by the fixation of sands of the natural divided foredunes through planting special species of trees and shrubs. The uniqueness of these efforts is accounted for by their spatial characteristics, i. e. scale. It was not local measures but an anthropogenic transformation of an area of seven thousand ha. Such large-scale changes in the environmental components require a special geoecological assessment from the perspective of their impact on the Spit's landscape and suitability for solving current problems of nature management and spatial planning.

Topographic maps of a scale of 1:25 000 drawn in 1859, 1936, and 2010 were used as a tool to assess the vulnerability of the Curonian Spit's landscape components. In the course of digitalising the cartographic materials of the 19th and 20th centuries using symbol equalisation scheme developed at the Baltic Air Geodesy Company, data on the boundaries of vegetation, relief, coastline, road network, and residential area were entered in the GIS structure. The interval between studies coincides with the period of the most intensive transformation of the Curonian Spit's landscape, i. e. the artificial formation of the foredune, which started in the 19th century and continues to this day.

Historical materials describing clearances on the Spit, which activated aeolian processes and buried plots of land, roads, and even settlements in sand, date back to the 19th century. These processes are reflected on historical topographic maps (Fig. 3).

The rapid transfer of dunes caused changes in the relief of the Spit's coastline. These changes are shown on topographic maps of the 19th/20th centuries. In the area of non-fixed dunes near the village of Morskoye, it reached maximum values — 300 m (the methodology has a margin of error of 25 m) (Fig. 4).

An analysis of topographic maps makes it possible to track the changes in vegetation relating to the dune fixation. The data of digitalised maps can be instrumental not only in calculating the area of vegetation cenoses (forests and meadows) but also in visualising their spatial dynamics (fig. 5).



a *b*

Fig. 3. Results of aeolian erosion on the Curonian Spit according to a 1859 map:
a — buried settlements (old location of the village of Kunzen and the inn);
b — buried old road and a new road built in the newly formed saddle along the lagoon

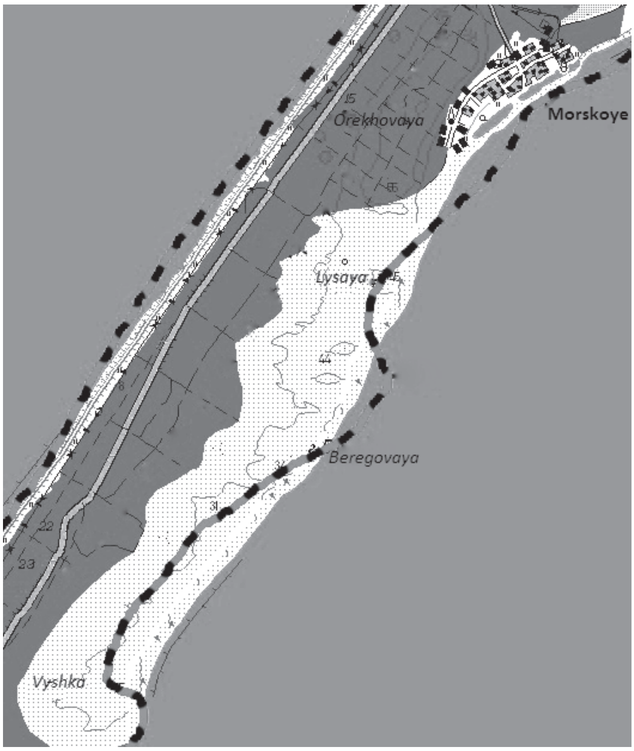


Fig. 4. Changes in the coastline near the village of Morskoye on the Curonian spit (dash line shows the coastline of the 19th century topographic maps)

Table 3 shows the results of calculating the areas of different vegetation types and residential territories on the Curonian Spit.

The analysis shows that the past 150 years saw a fivefold increase in the forest area. This process was accompanied by population and cultivation of the Spit by local residents, which lead to an almost twofold increase in residential areas as compared to the 19th century. Therefore, the late 19th/early 20th century was a period of the most intensive human occupation and transformation of the Spit's natural components and landscapes. In the 21st century, the rates and dynamics of this anthropogenic impact persist.

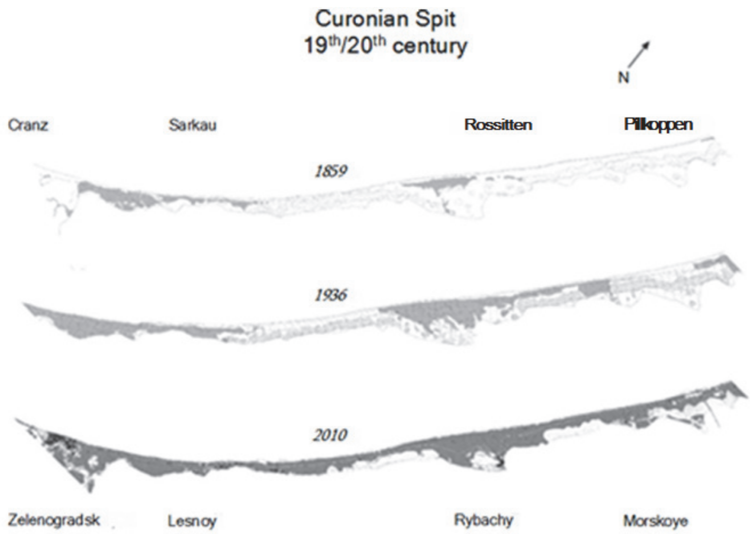


Fig. 5. Changes in the forest area of the Curonian Spit in the 19th/21st centuries

Table 3

Areas of different vegetation types and residential territories on the Curonian Spit, (hectare)

Territory	19th	20th	21st	Changes,% (21st/19th)
Forests	1,037	2,683	5,549	535
Meadows	265	910	850	321
Dune sands	6,009	911	1736	29
Residential territories (villages)	47	129	111	236

The algorithm used above for the whole territory of the Kaliningrad region was applied to solve the problem of assessing the temporal changes in the vulnerability of the Curonian Spit's landscapes. An analysis of the topographic maps of the Curonian Spit used three parameters:

the surface slope — local digital relief models were created to calculate slopes based on the data of the digitalised horizontal control (19th/20th centuries);

types of land showing the spatial changes in forest, meadow, and dune areas (dune sands were considered as the most vulnerable category of lands);

distance to the sea.

According to the calculations, the integrated vulnerability index of the Curonian Spit landscapes is characterised by a positive trend. Using the calculation methodology in a GIS framework made it possible to identify areas of different vulnerability to physical impact (Fig. 6).

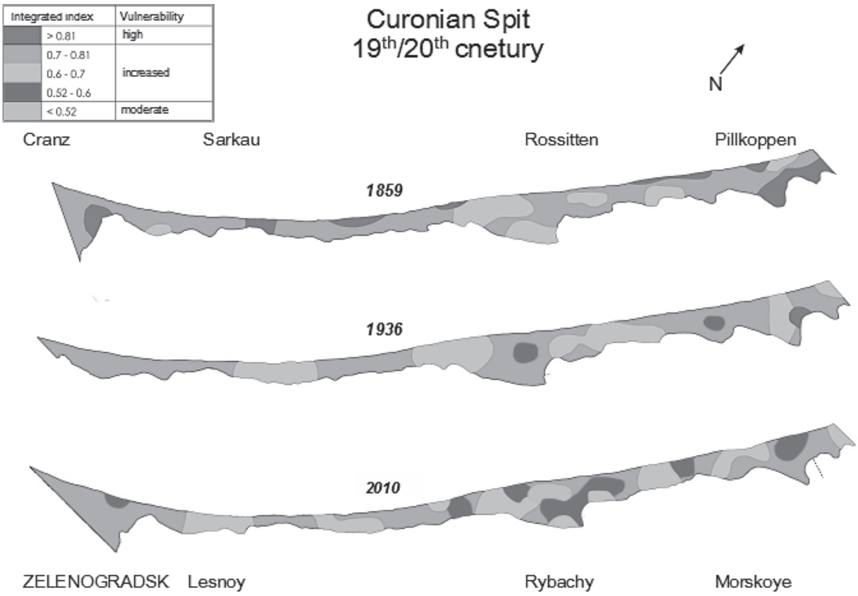


Fig. 6. Changes in the index of vulnerability to physical impact on the Curonian Spit

In the 19th century, areas of high and increased vulnerability prevailed, where the integrated index ranged from 0.62 to 0.86 with a weighted average of 0.74. In the 20th century, highly vulnerable areas became a local phenomenon observed in the North of the Spit, whereas the central part was characterised by increased vulnerability. The integrated index ranged from 0.56 to 0.81 with a weighted average of 0.71. This trend continues to this day. Vast areas are still characterised by increased vulnerability, but some territories already belong to the moderate category, and high vulnerability sections are disappearing. In the 21st century, the integrated index ranges from 0.51 to 0.78 with a weighted average of 0.67.

There is a trend towards decreasing vulnerability. The measures aimed at the transformation of the Spit's relief and fixation of the dunes are a good example of effective optimisation of regional nature management. It is important to understand that the trend towards decreasing vulnerability of the Curonian Spit's landscapes to physical impacts shown by the calculations was not brought about by natural temporal changeability of environmental components. On the contrary, it is a result of well-thought-out natural protection measures to transform the Spit's natural landscapes.

The proposed methodology of assessing landscape vulnerability to anthropogenic pressures and the results obtained can be used to optimise the existing system of assessing of environmental impact and to integrate environmental approaches in the Russian system of spatial planning.

The findings of this study can be used in the Kaliningrad region. Let us compare the current spatial planning schemes with the spatial model of vulnerability area distribution. Superimposing makes it possible to assess probability of conflicts between industrial facilities and the environment (Fig. 7).

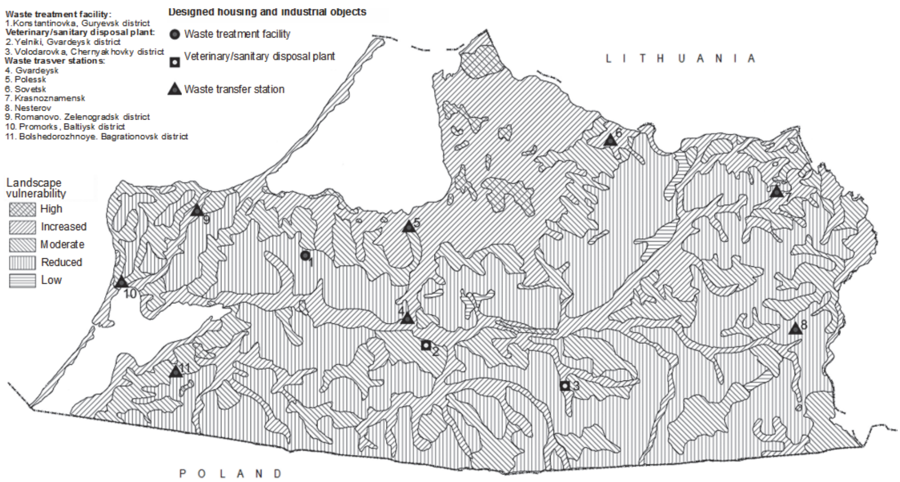


Fig. 7. Superimposition of designed housing and industrial objects on the areas of landscape vulnerability to anthropogenic pressures

In particular, it shows that the construction of certain housing and industrial objects is undesirable, since they would be located in increased vulnerability areas. These include veterinary and sanitary disposal plants in the village of Yelniki of the Gvardeysk district and the village of Volodarovka in the Vhernyakhovsk district and the waste transfer stations in the towns of Gvardeysk, Polessk, Sovetsk, and Krasnoznamensk. Therefore, the existing regional spatial planning schemes do not fully meet the criteria of environmental safety and facility location.

Three is a need to consider several scenarios for resolving such situations. The first one suggests analysing alternative location variants — building the facilities beyond the areas of high and increased vulnerability. The other requires additional conservation measures and monitoring at the stages of design, exploitation, and preservation of objects erected at the initial location.

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